Mapping the CMB at High-Frequency with Kinetic Inductance Detectors on the South Pole Telescope

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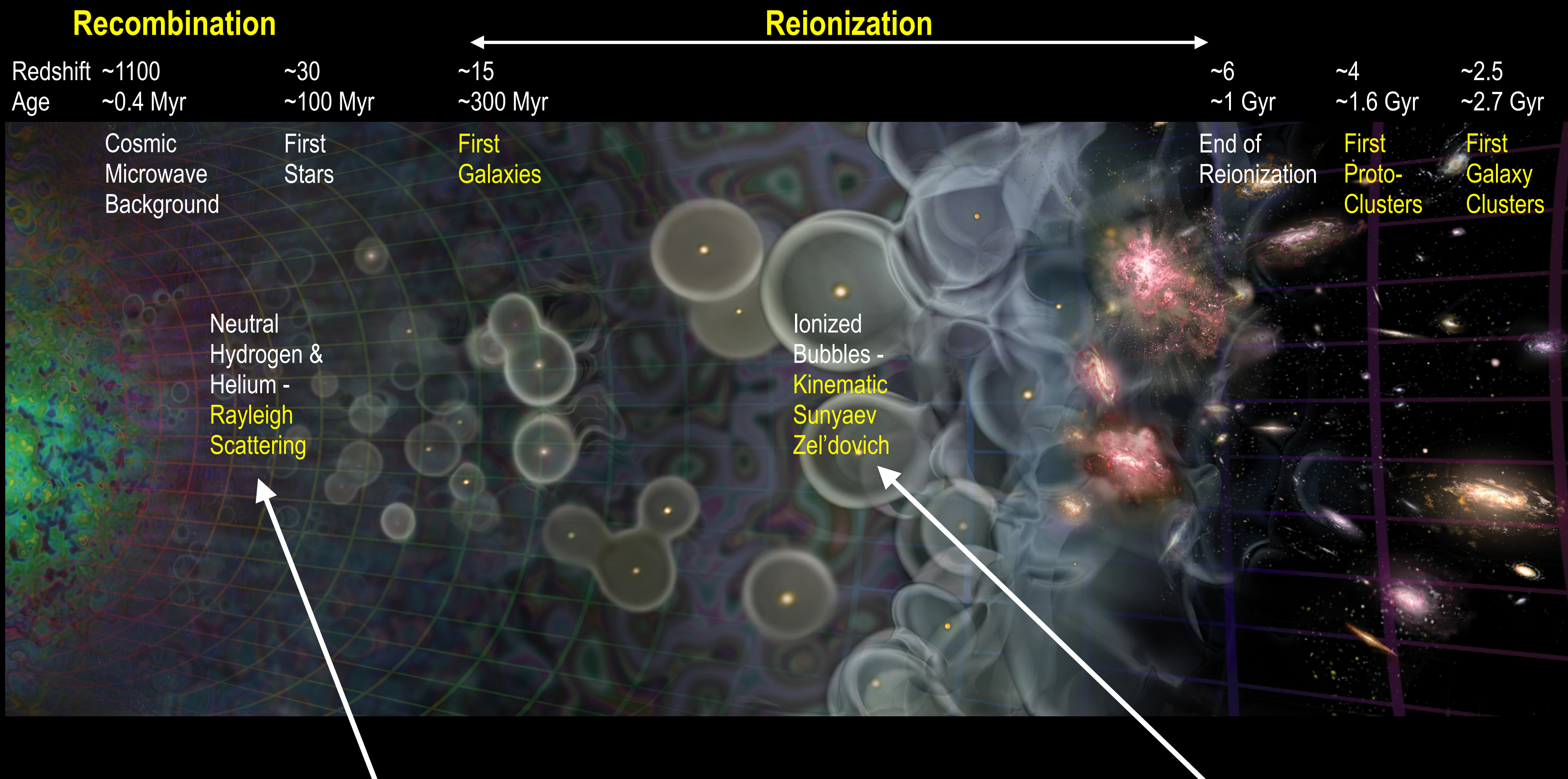
Matt Dobbs
Kirit Karkare
Srini Raghunathan
Maclean Rouble
+ many others!

Reionization, Recombination, and the CMB



Rayleigh scattering:

CMB photons scatter on neutral H and He at a redshift after recombination, imprinting additional cosmological information in the CMB anisotropy.

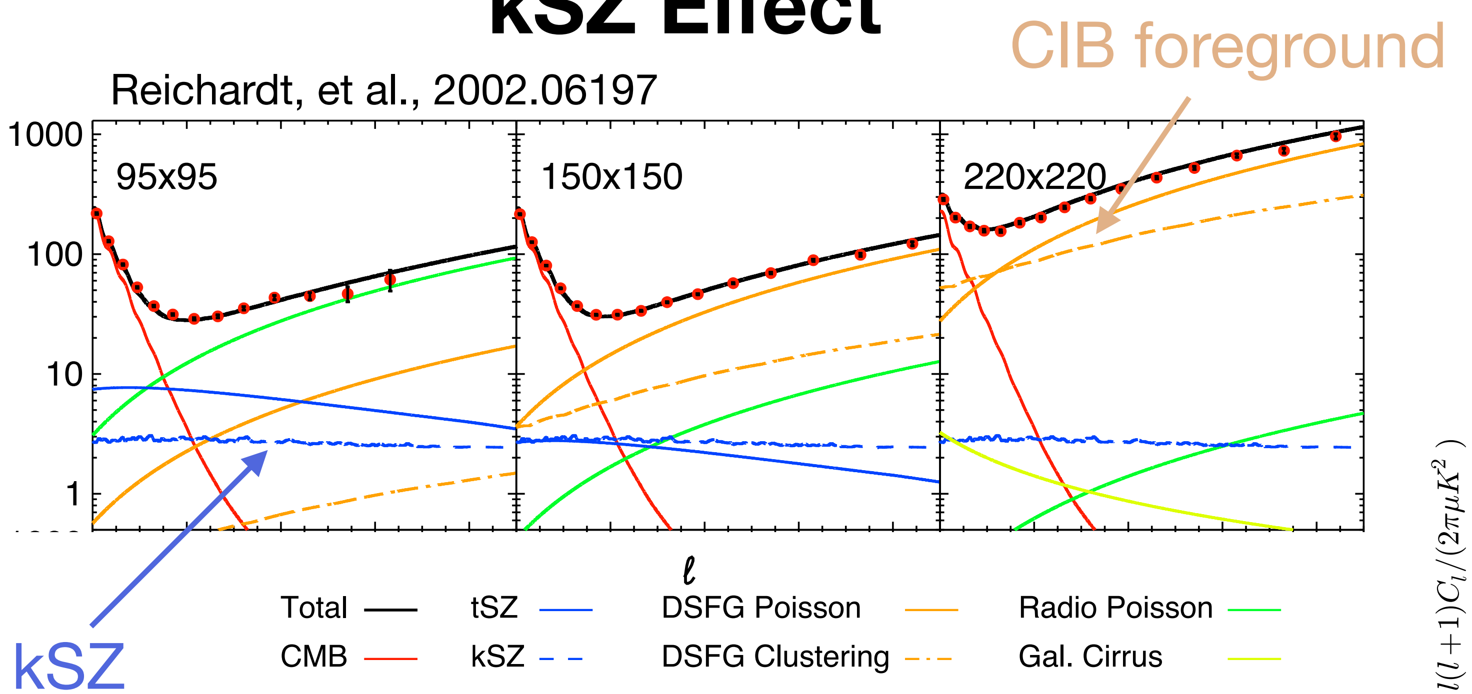
Patchy kSZ effect:

CMB photons scatter on expanding bubbles of ionized gas, imprinting ionization history in anisotropy.

Science with High-Frequency CMB Measurements

kSZ Effect

Reichardt, et al., 2002.06197



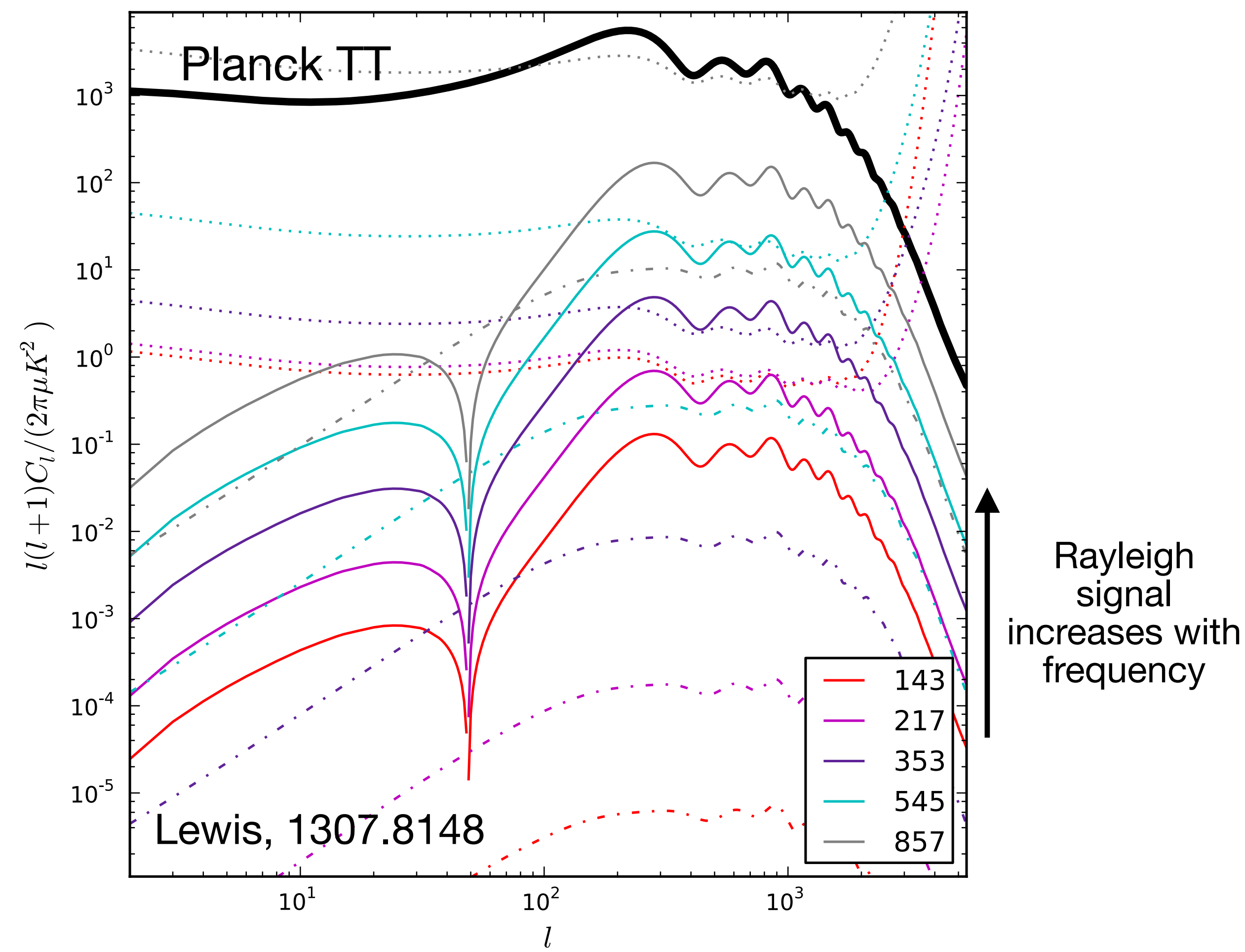
- Measurement requires *high resolution* and *low noise at frequencies >150 GHz* to remove CIB foreground.

- Science drivers:

  1. Independent CMB-only probe of duration and redshift of reionization

  2. Totally independent measurement of optical depth to reionization: improves limiting systematic for ***neutrino mass*** and ***light relics***

Rayleigh Scattering



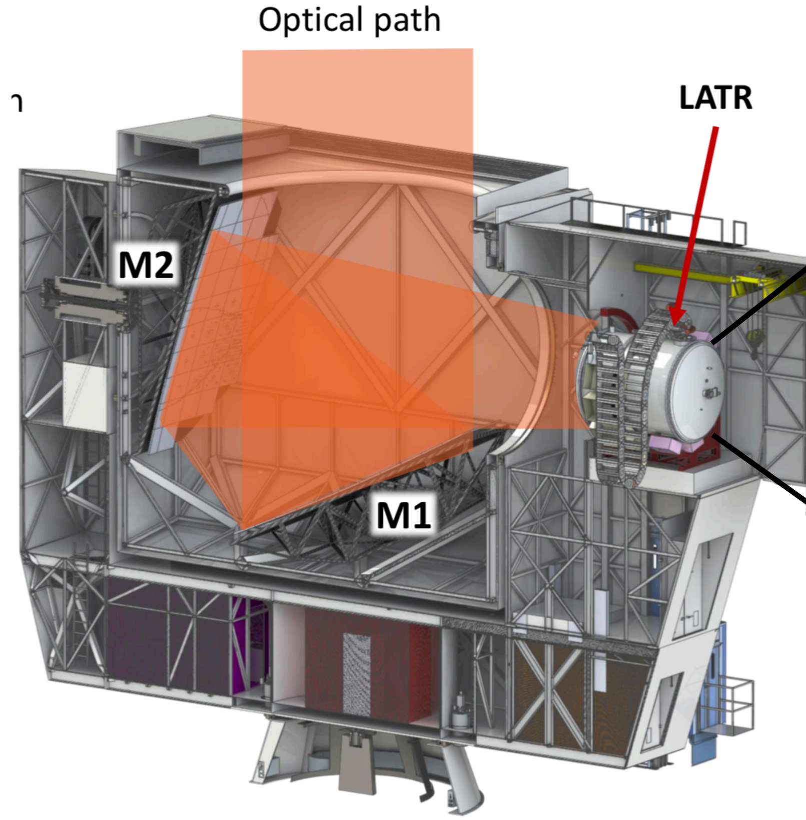
- Rayleigh cross section frequency scaling strongly favors observing bands >150GHz:

$$\sigma_R(\nu) \approx \sigma_T \left[\left(\frac{\nu}{\nu_{\rm eff}}\right)^4 + \alpha \left(\frac{\nu}{\nu_{\rm eff}}\right)^6 + \beta \left(\frac{\nu}{\nu_{\rm eff}}\right)^8 + \ldots \right]$$

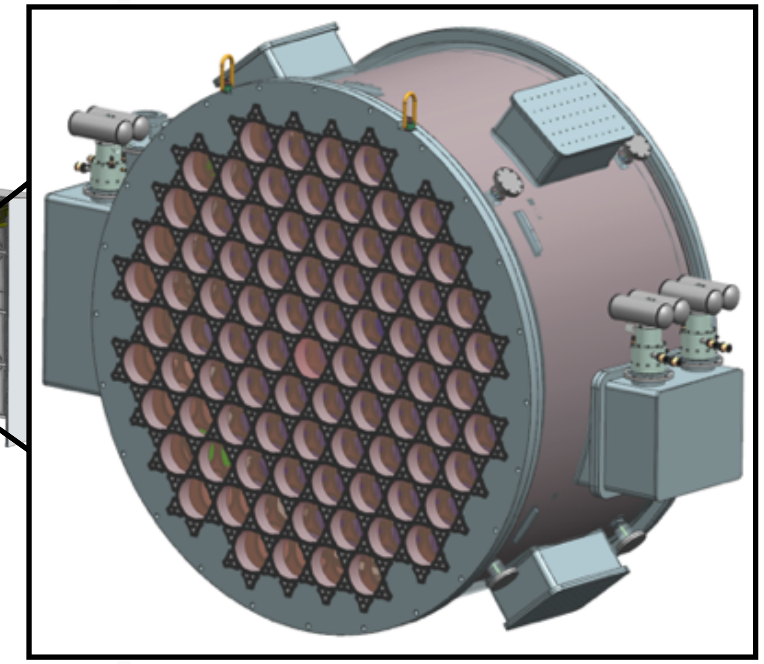
- Science driver: ***beat cosmic variance*** in CMB-based cosmological parameters

Future Experimental Landscape

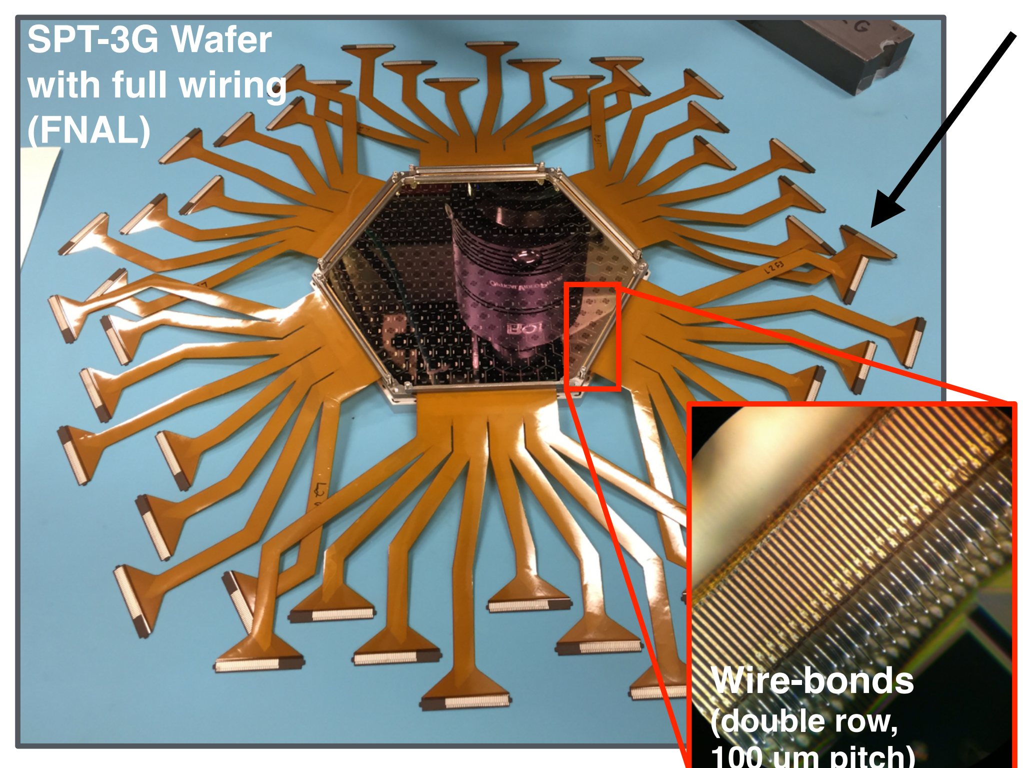
- CMB experimental landscape in the 2020s is dominated by CMB-S4 and its predecessors (e.g. SPT-3G, BICEP Array, Simons Observatory)
- CMB-S4 has 500,000 TESs observing at 27-270 GHz with complex cryogenic multiplexing electronics
- Conservative and costly design choices have generally been emphasized to reduce risk and eliminate R&D… ***opportunities to innovate still exist!***
- ***Example:*** TES detector density limited by available space for wirebonds on perimeter…



CMB-S4 / Simons Observatory LAT

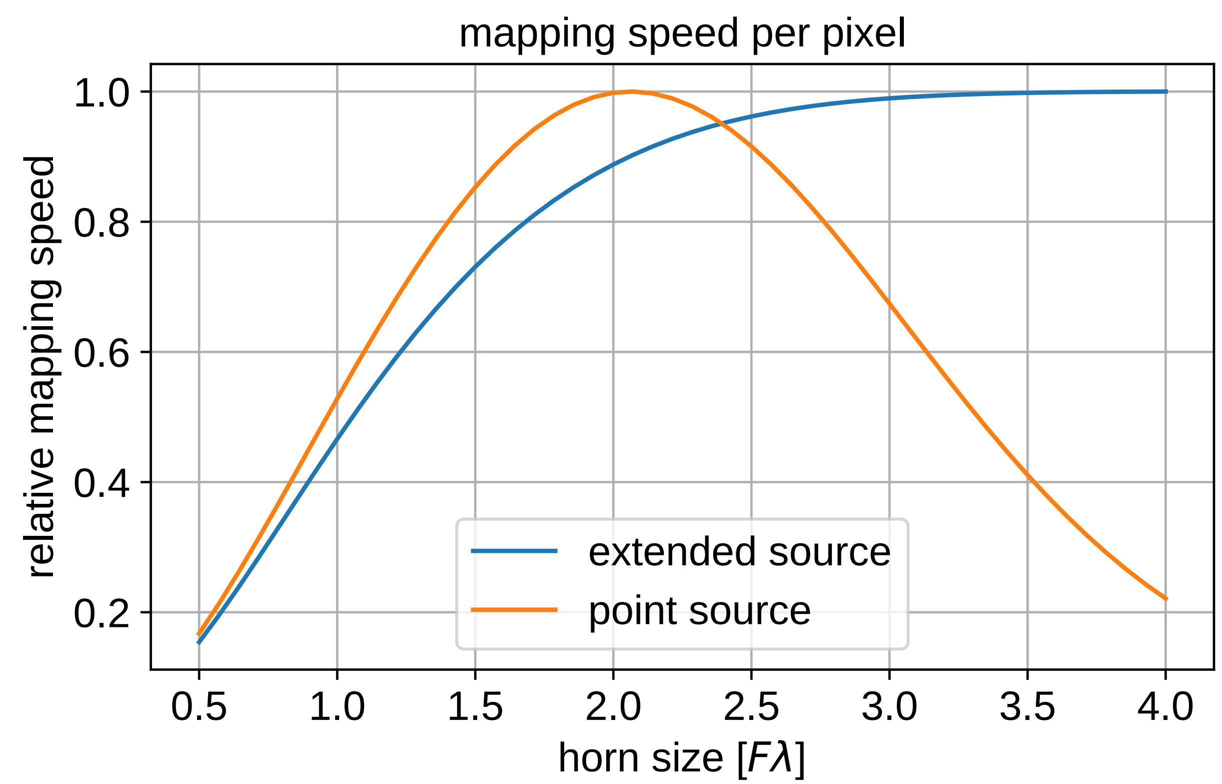

CMB-S4 85-tube cryostat concept

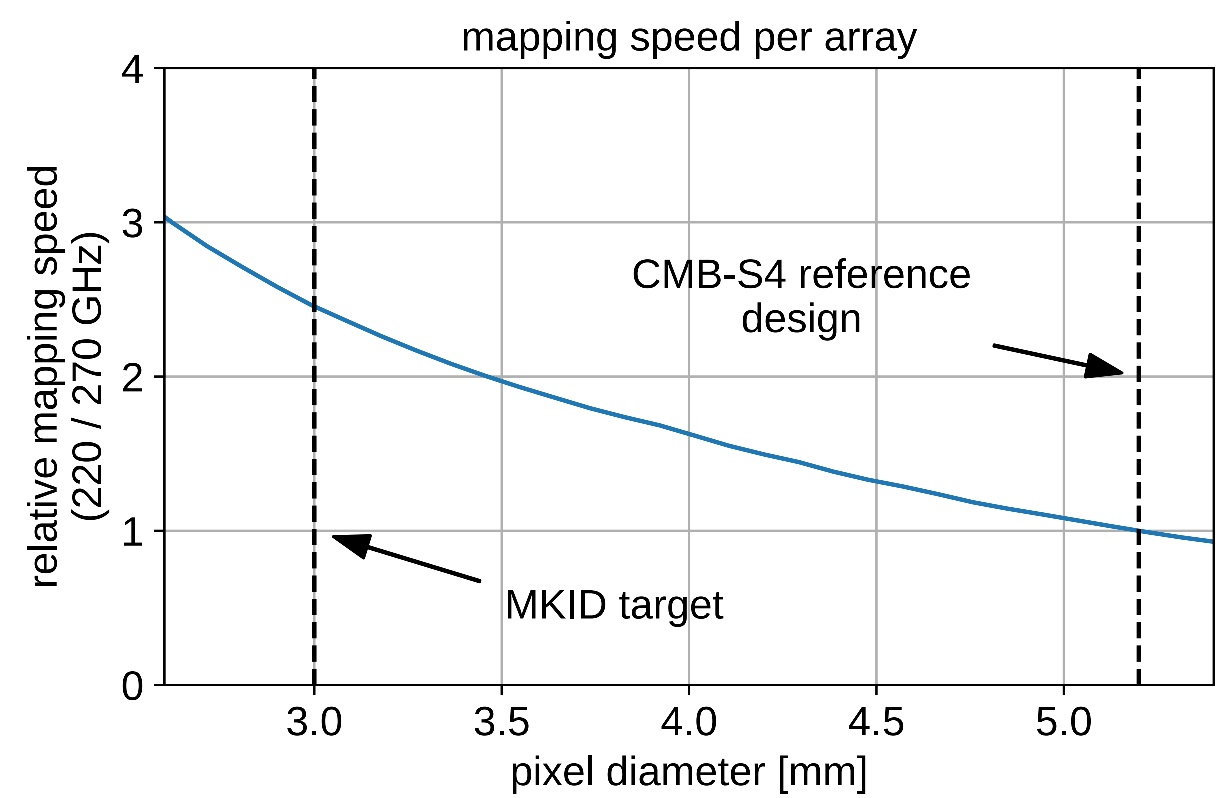
flex cables to cryogenic multiplexers



MKID Advantage for CMB

- Mapping speed ***per pixel*** optimized for ≥ 2 $F\lambda$
- But smaller pixels enable more detectors per array, so mapping speed ***per array*** maximized for small pixels
- CMB-S4 220/270 GHz dichroic band is limited to ~2000 detectors / wafer
- 2-3x increase in sensitivity possible by moving to smaller pixels





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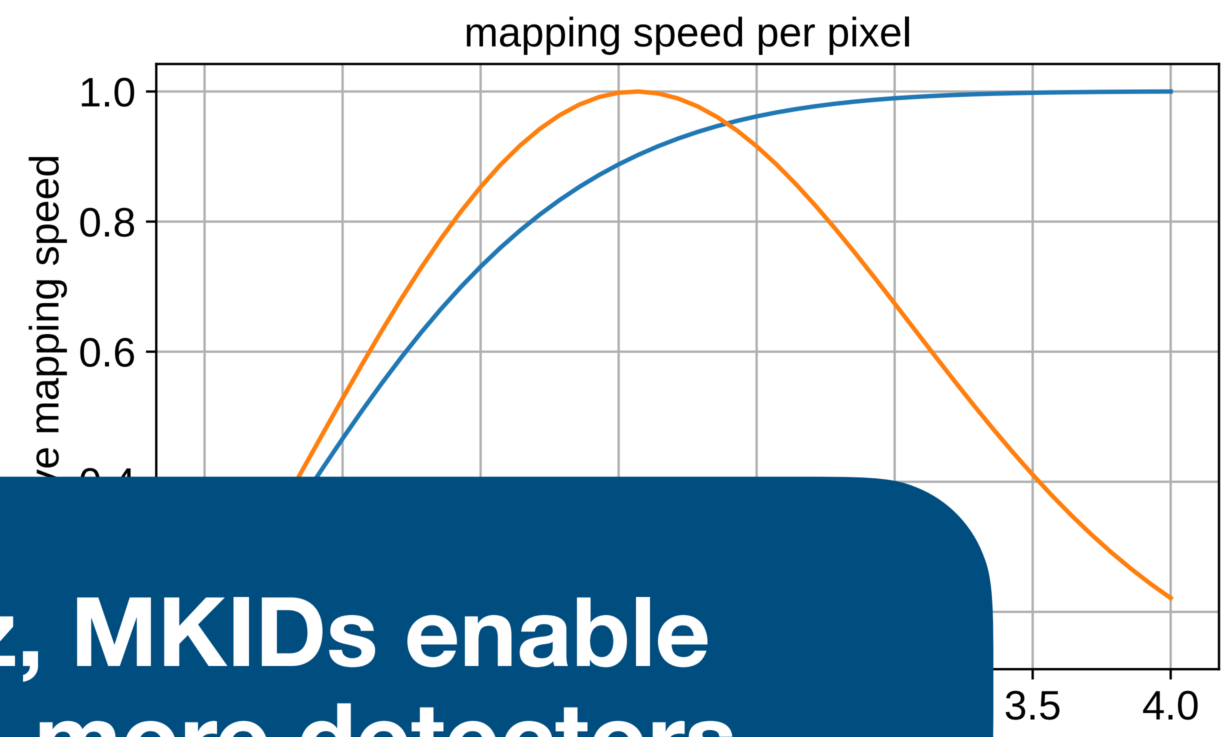
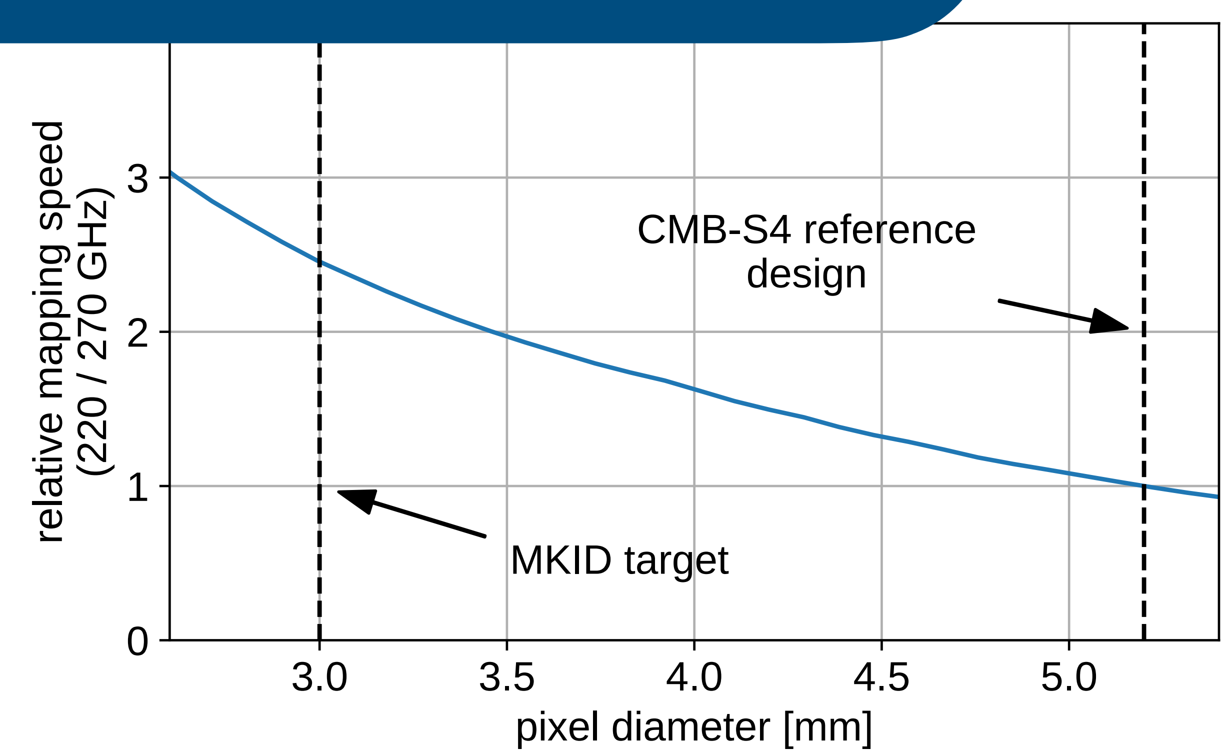
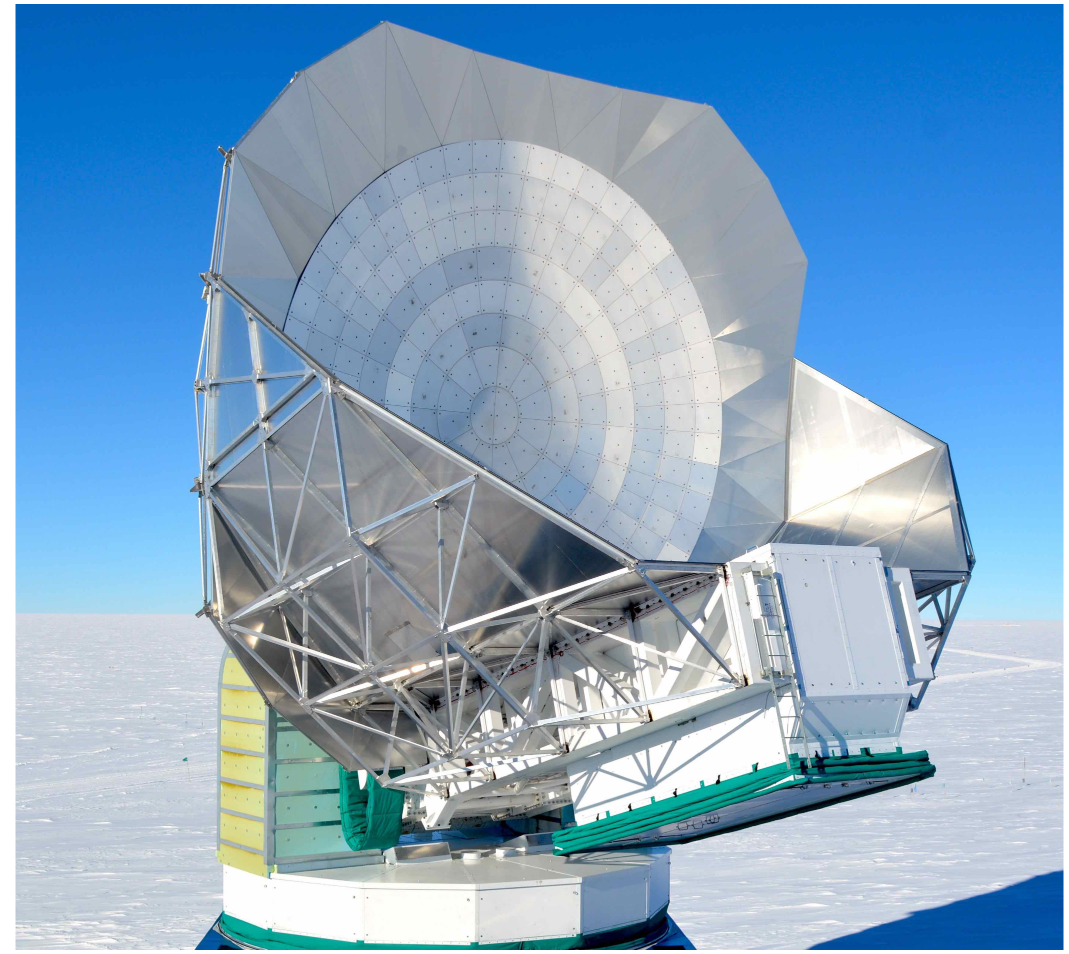


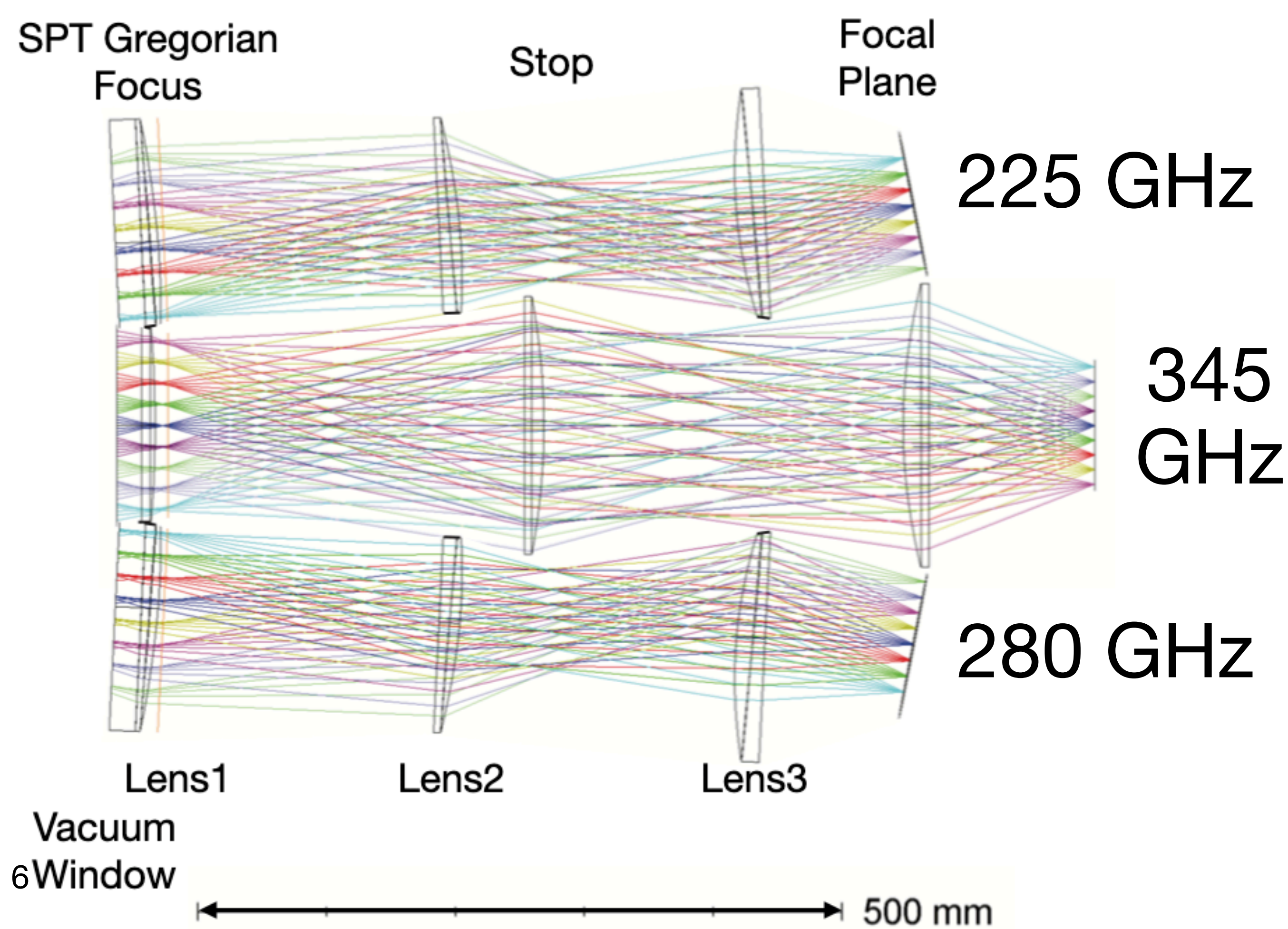
Above 150 GHz, MKIDs enable denser arrays + more detectors



SPT-4 Concept

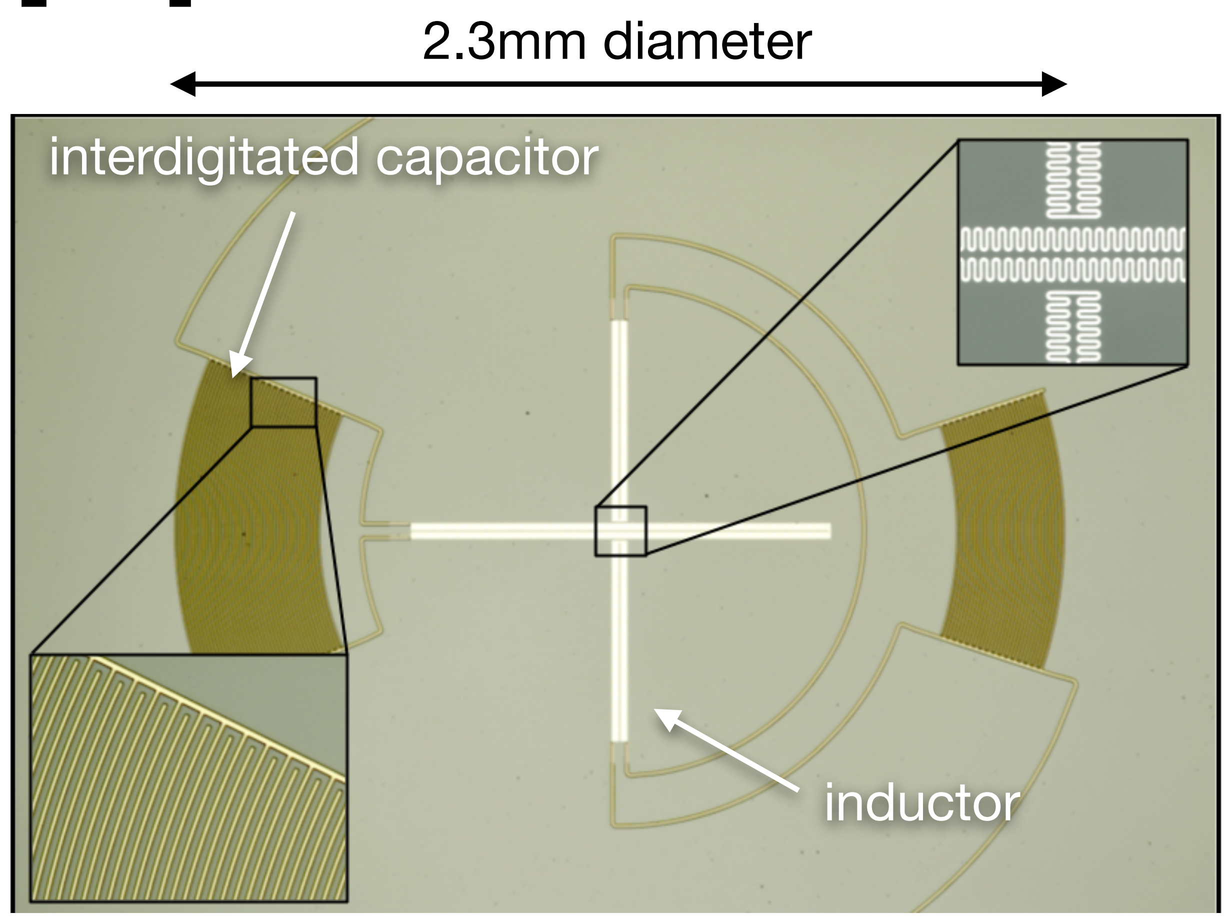
- New cryostat on South Pole Telescope (SPT) with MKID focal plane for reionization science + galaxy clusters + Rayleigh scattering
- 24,000 detectors observing at 225, 285, and 345 GHz
- Modular optics tubes for future upgrade to spectrometer arrays (see K. Karkare talk)
- ***MKIDS enable reaching some S4-level science targets faster and at much lower cost***

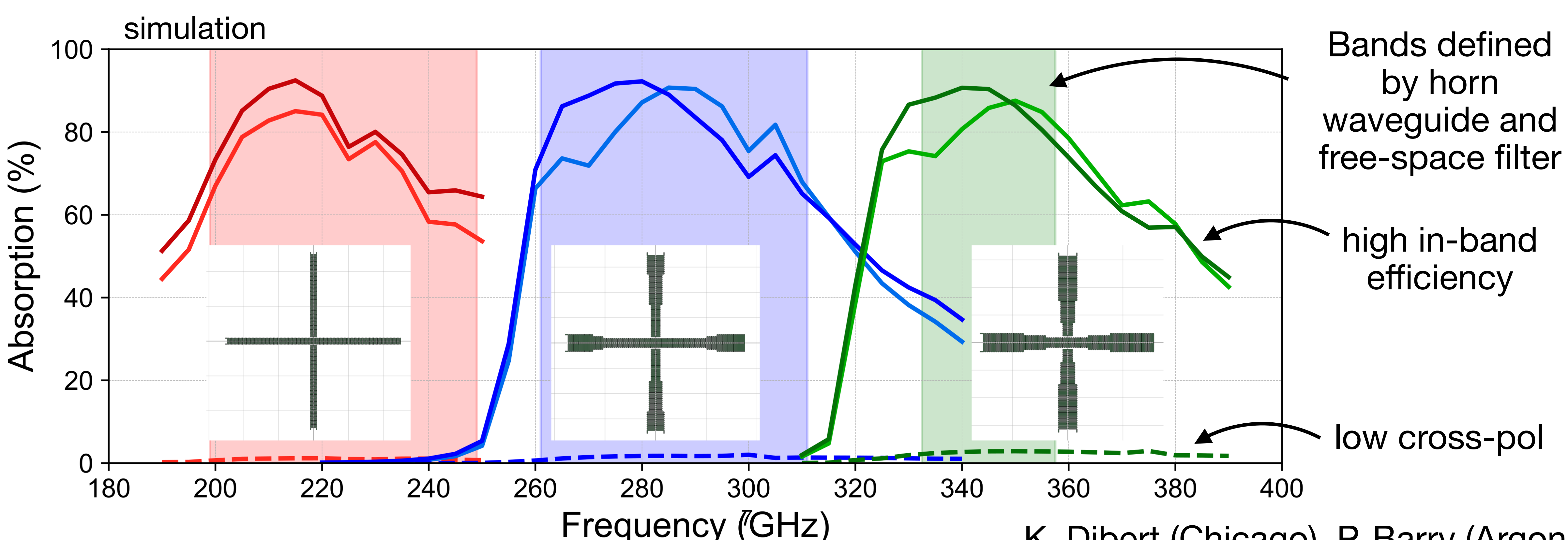




Detectors for SPT-4

- See P. Barry talk this session for more details!
- Horn-coupled, dual-polarization pixel with direct absorption
- Compact design with simple fabrication achieves 2.3mm pixel diameter across all three bands with 1-2 GHz readout bandwidth
- 225 GHz single-pixel devices fabricated and tested in the lab, design developed and simulated for 285 and 345 GHz
- ***7 wafers with 3500 detectors each***



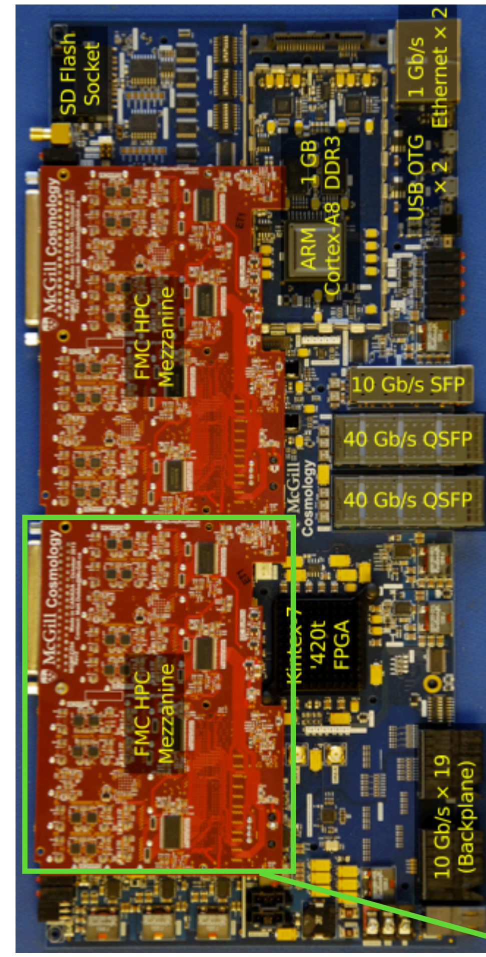


K. Dibert (Chicago), P. Barry (Argonne)

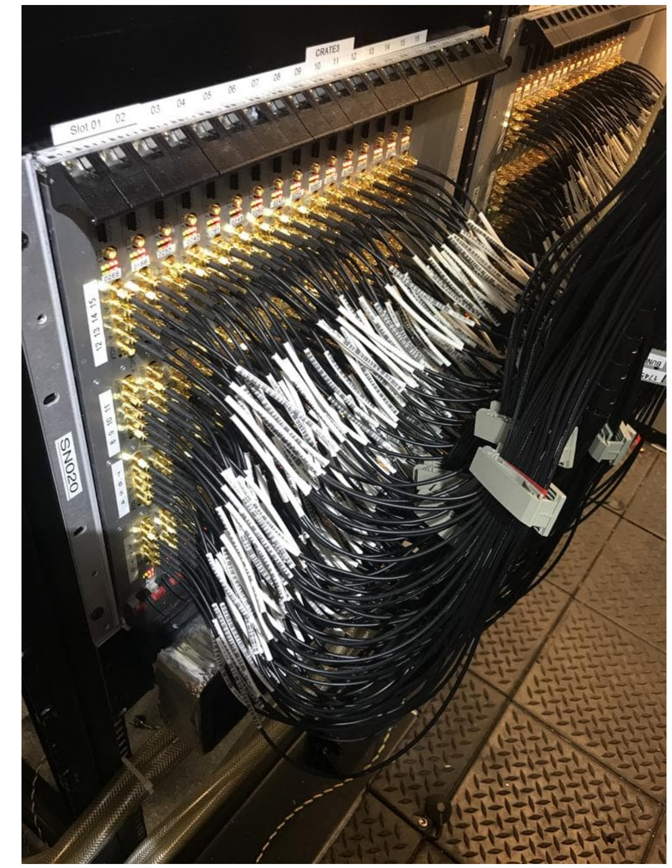
Next-Generation Microwave Readouts

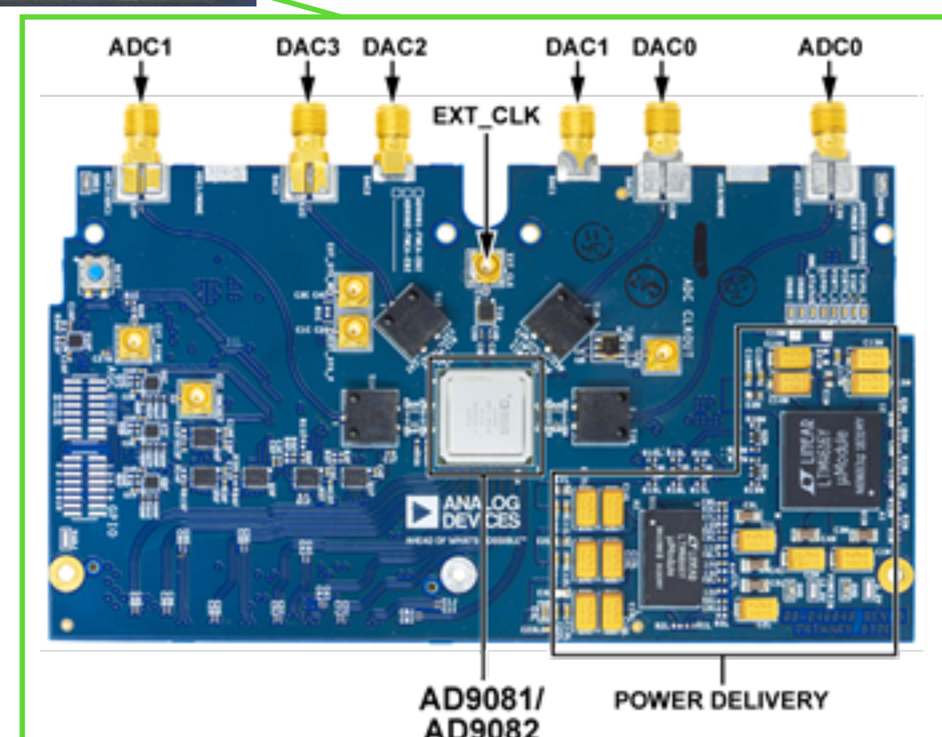
- Adapting “ICE” platform developed by McGill for readout of TESs in SPT-3G and radio receivers in CHIME
- Digital feedback in TES firmware for linearizing SQUIDs is straightforward to adapt to tone-tracking
- Maintain legacy motherboards while swapping RF mezzanine based on the AD9082 chip:
    - 4x DACs (12 GSPS) and 2x ADCs (6 GSPS) per board, supporting 2048x multiplexing at baseband
- Enables reuse of full software stack developed for SPT-3G TESs: major reduction in effort!

ICE motherboard



Hundreds of ICE boards deployed in the field (1608.06262)





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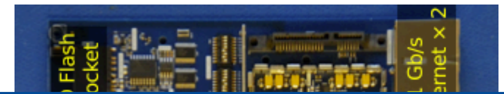

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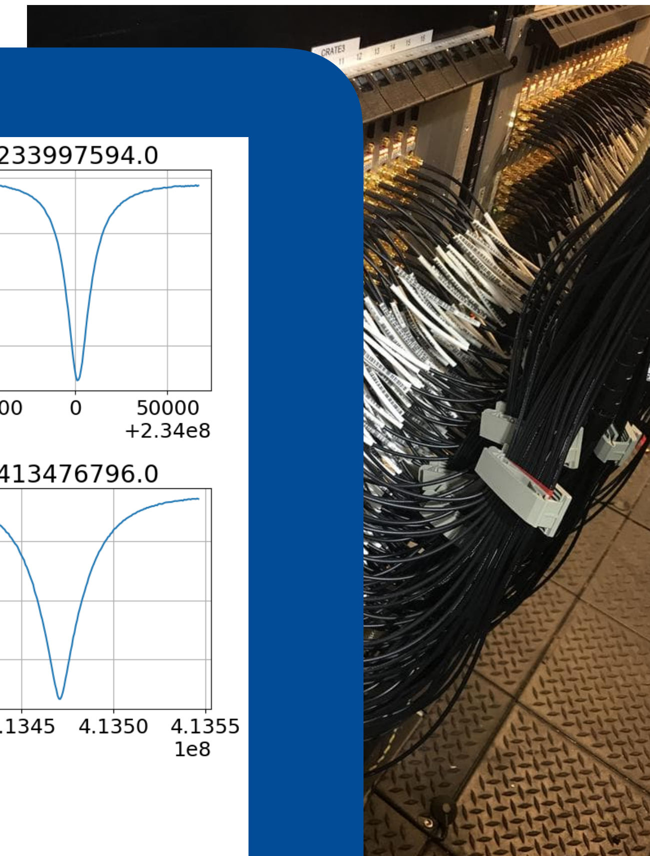
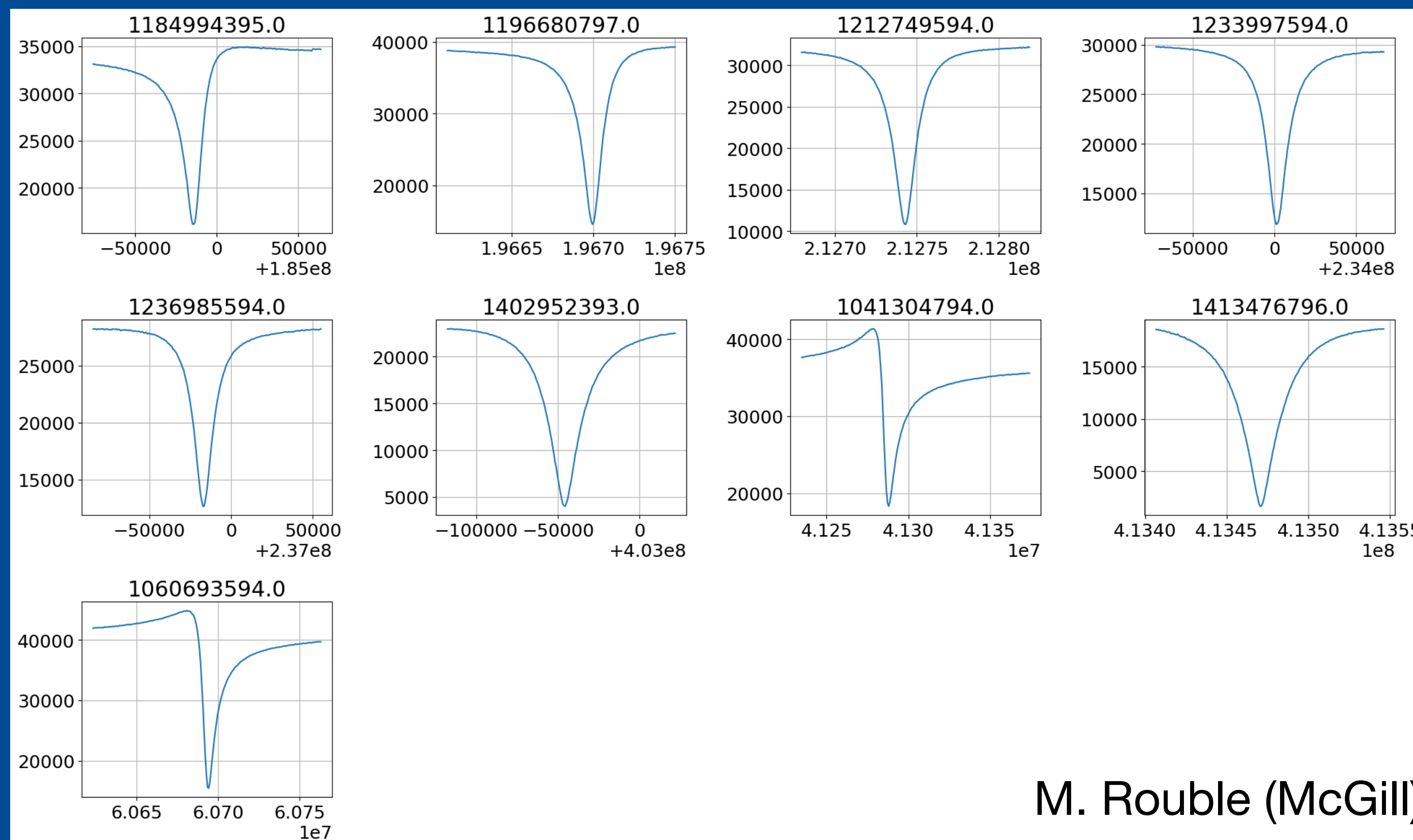
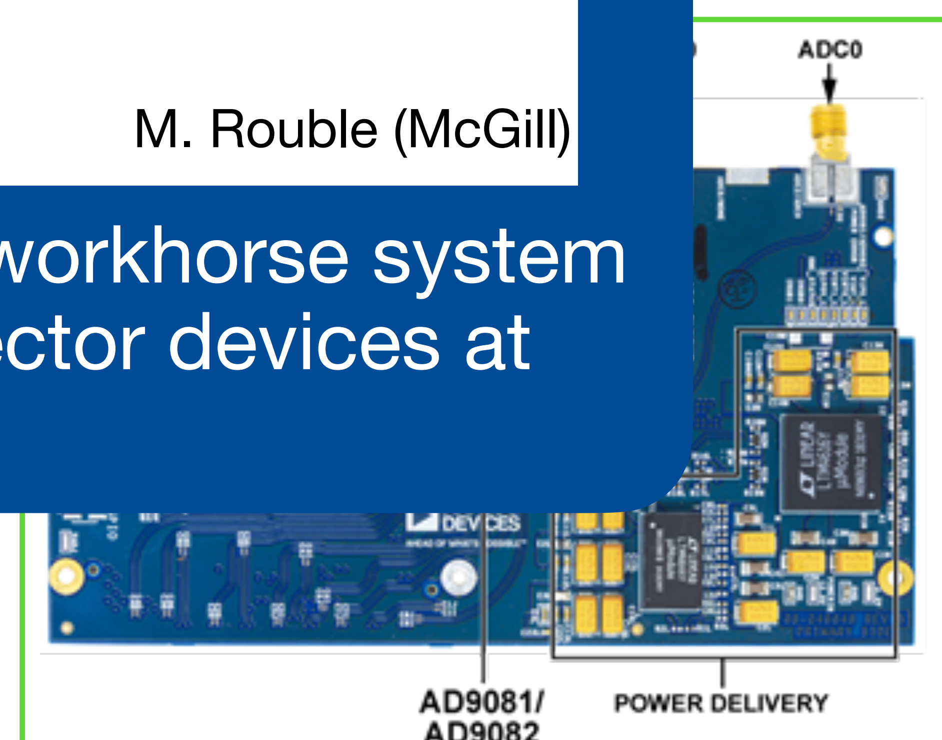


- Adapting "ICE" platform developed
  by McGi
  SPT-3G
  CHIME
- Digital fe
  linearizin
  straightf
  tracking
- Maintain
  swappin
  the AD9
  - 4x DA
    (6 GS
    2048x
- Enables
  develope
  reduction in effort!



M. Rouble (McGill)

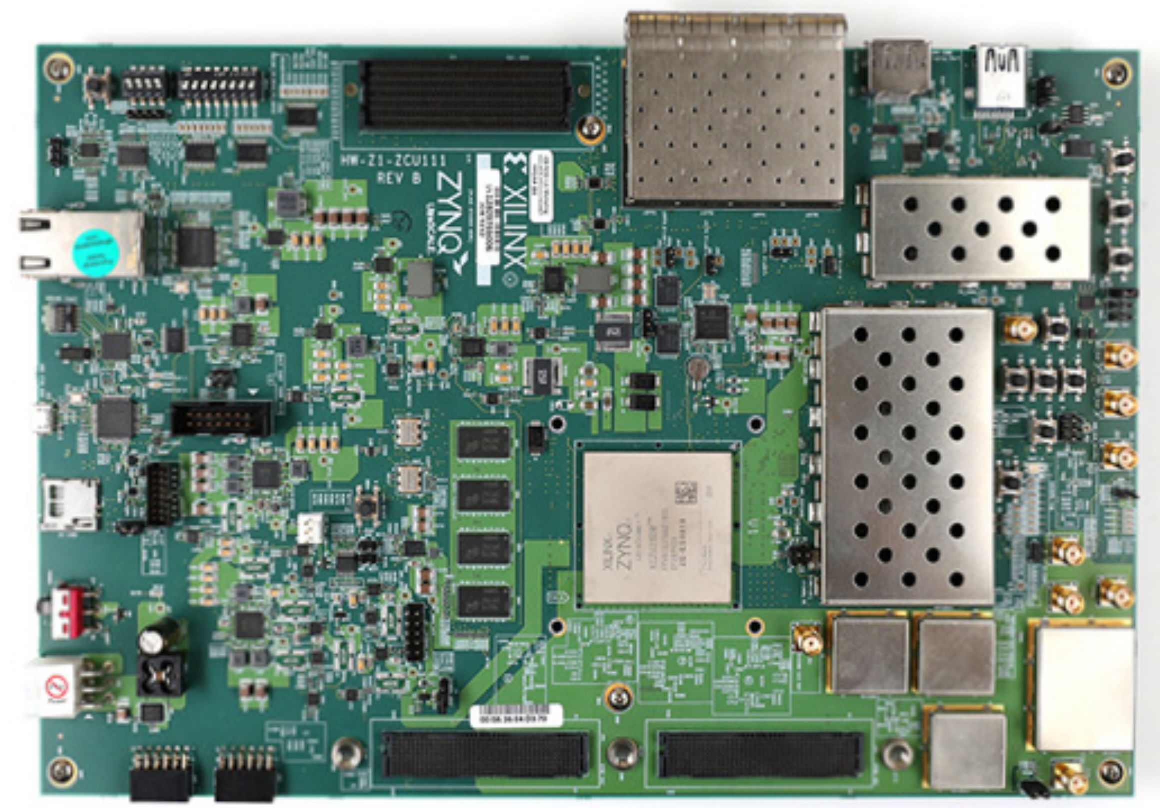
Already used as our primary workhorse system for characterizing test detector devices at Fermilab

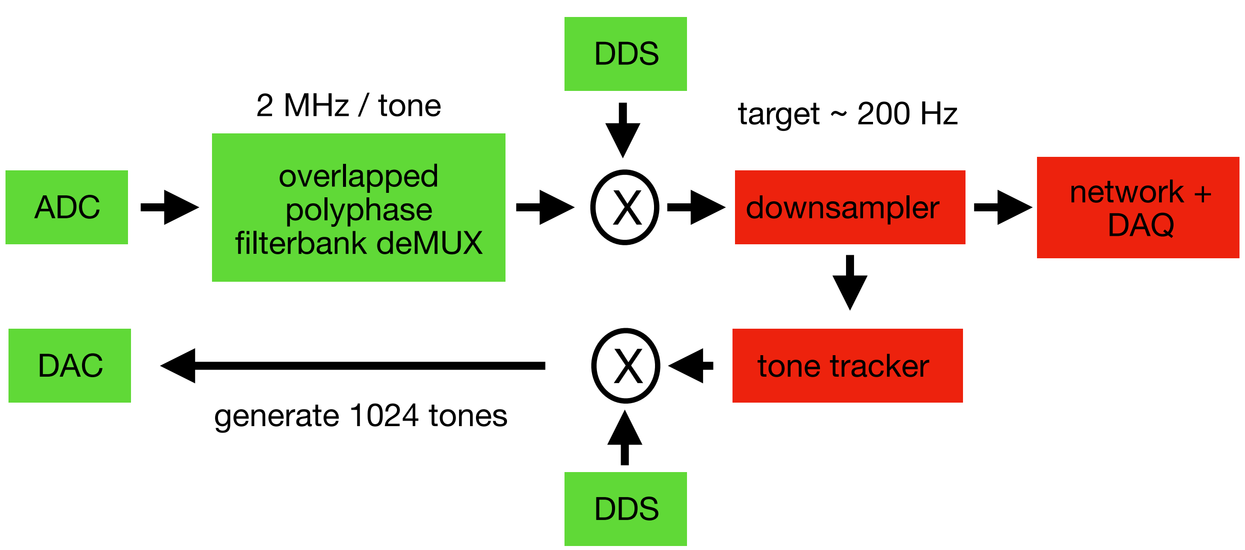


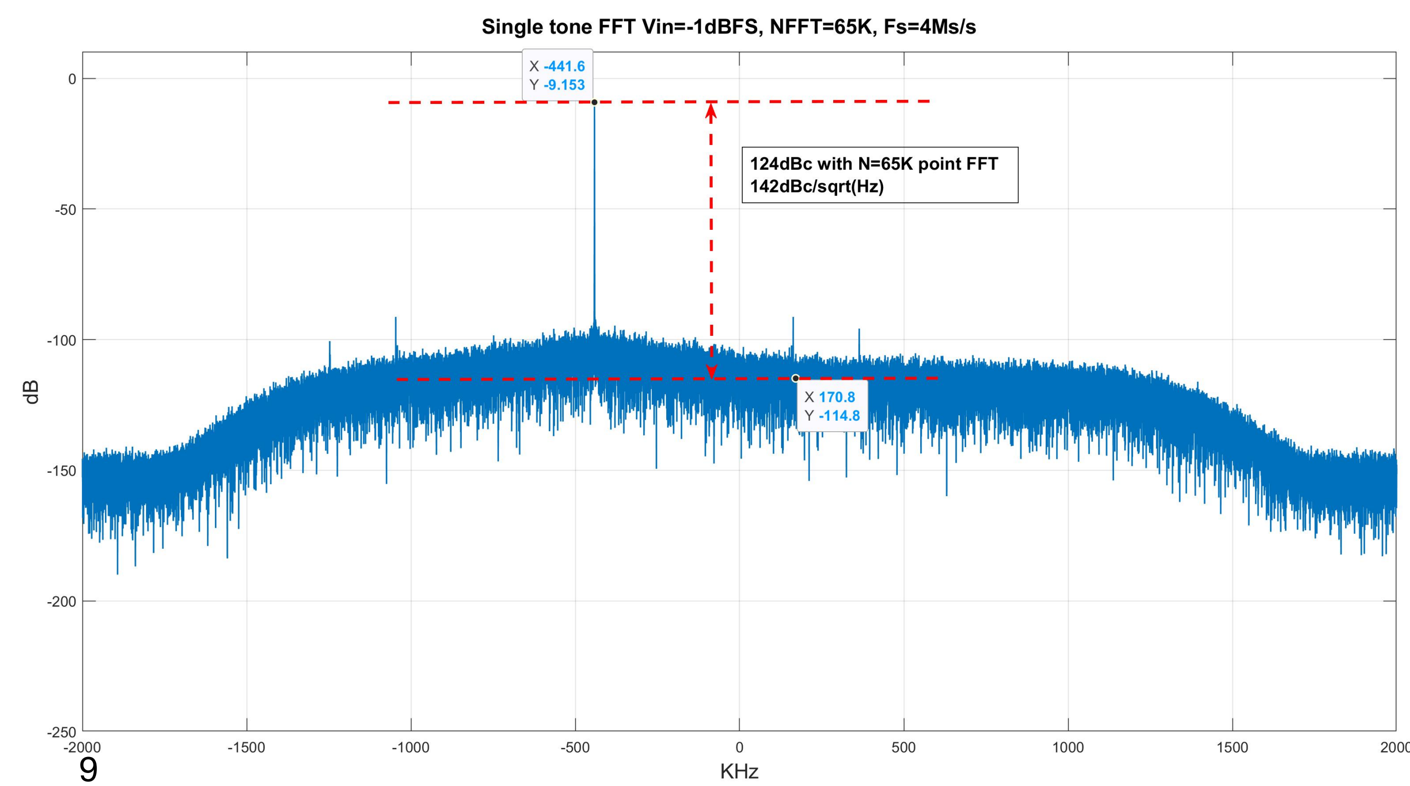
RFSoC Readout Platform

- Xilinx UltraScale+ RFSoC ZCU111 demo board (now old) has 8x ADCs (DACs) at 4 (6) GSPS
- MKID firmware developed at Fermilab (G. Cancelo, L. Stefanazzi, ++) demonstrated 1024x MUX over 2GHz bandwidth with adequate noise performance (path to 8k channels / board)
- Tone-tracking capability in development; drastically improves detector linearity, which is important for ground-based operations
- Key enabling technology for much larger MKID arrays in the future!

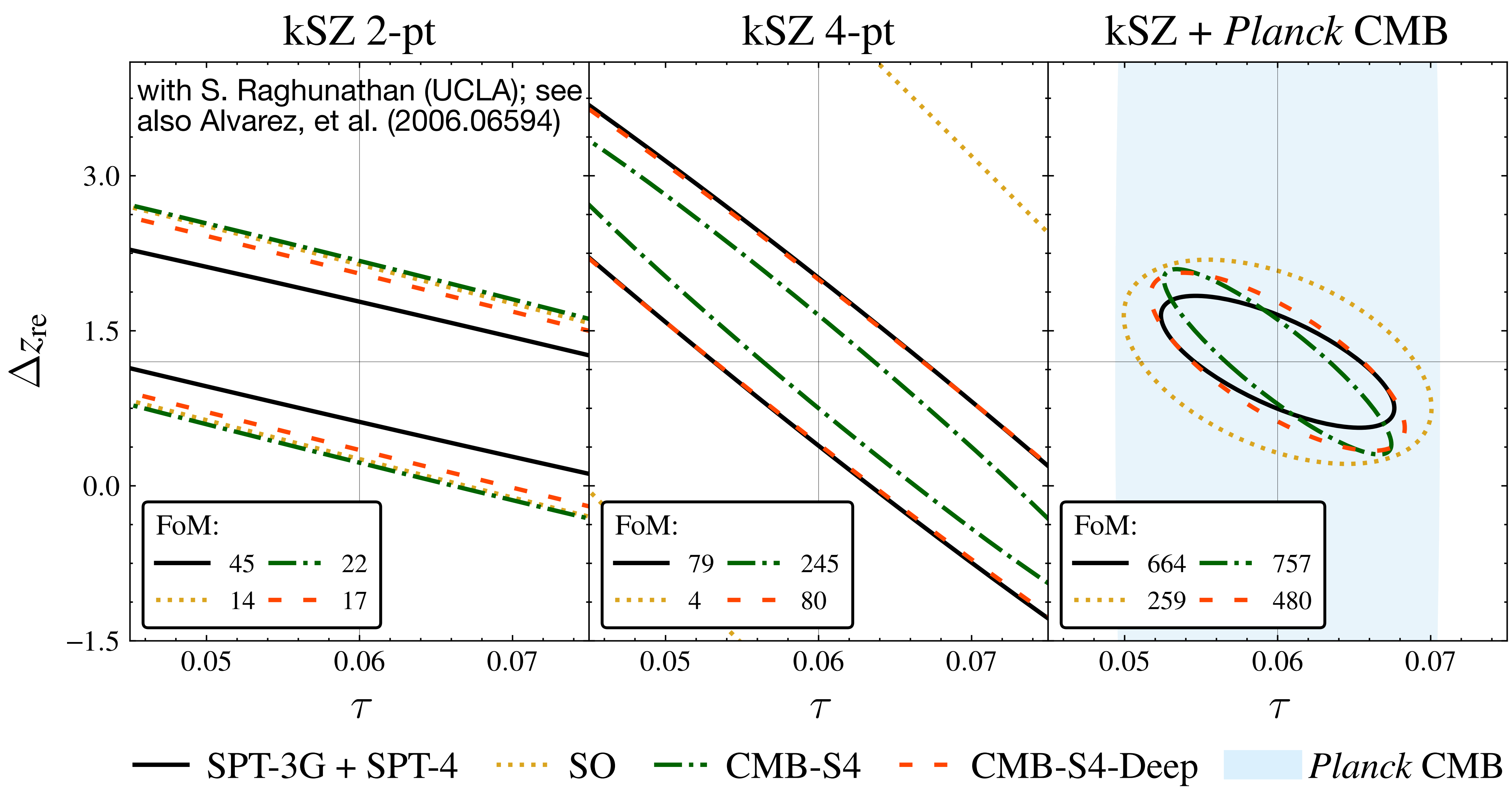
Xilinx ZCU111





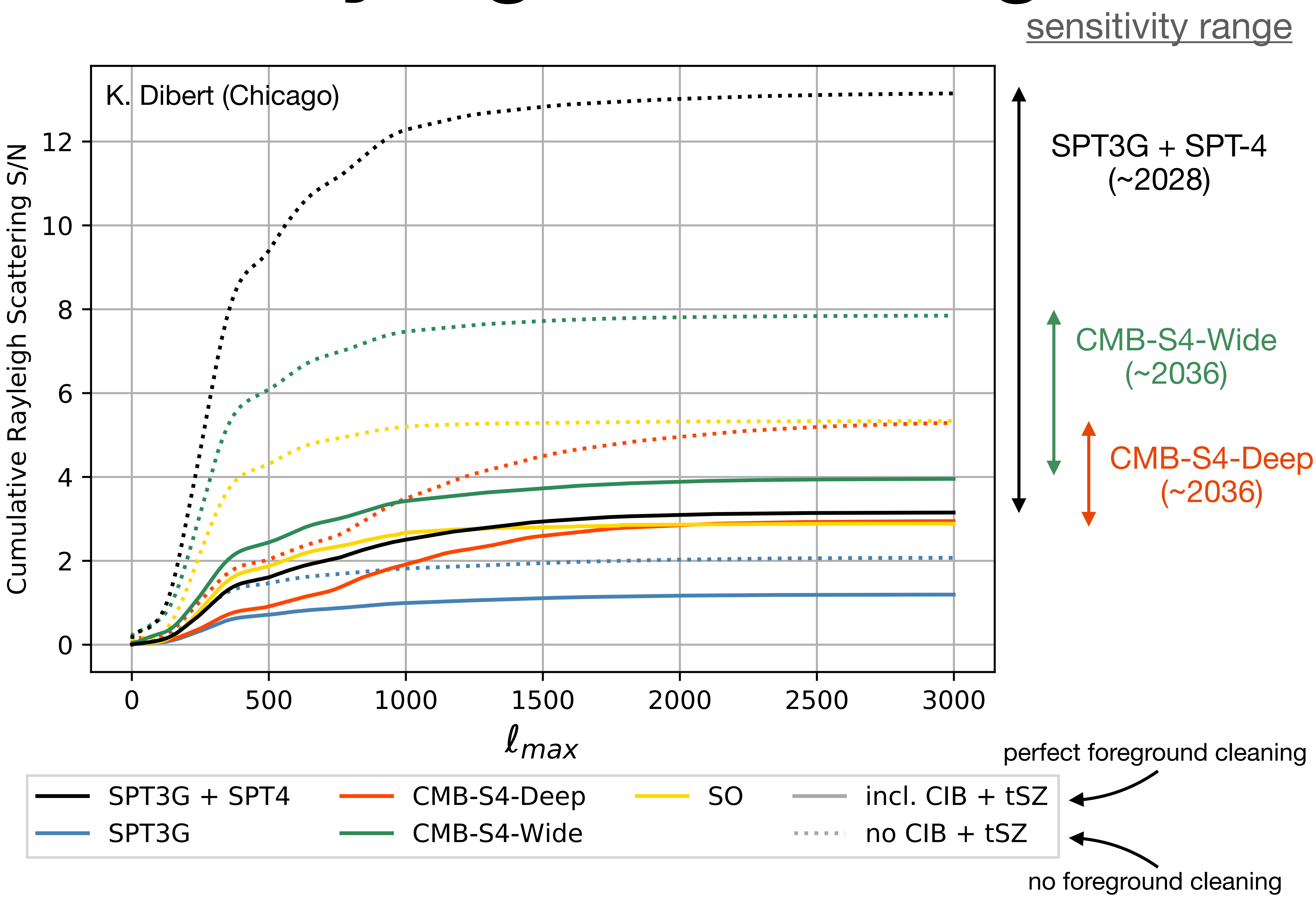


SPT-4: kSZ and Reionization



Combined kSZ 2-pt and 4-pt function constrains optical depth comparable to Planck, but totally independent → improves neutrino mass from CMB

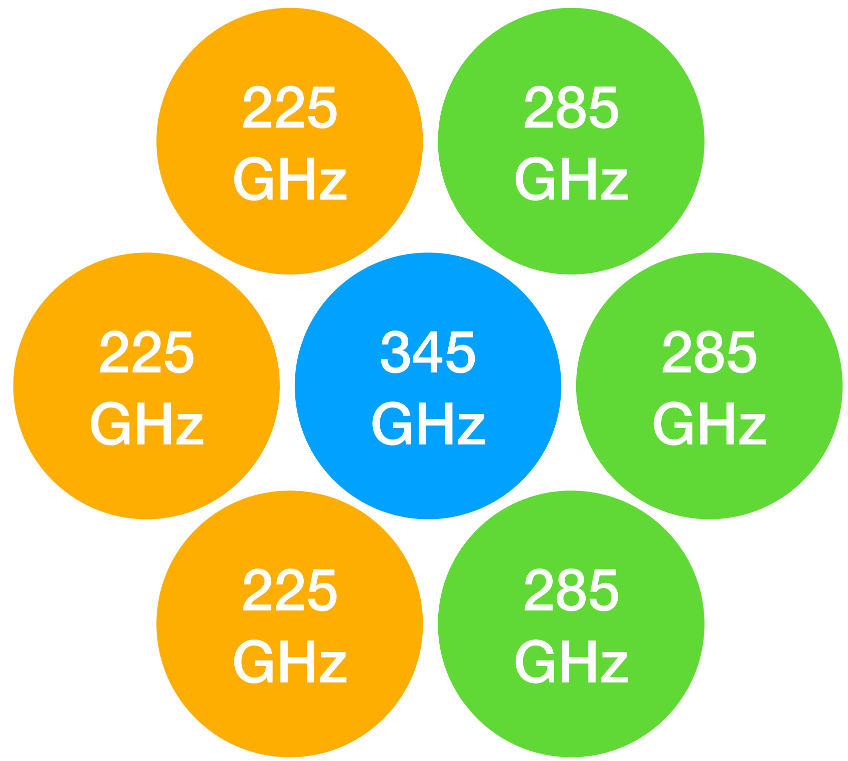
SPT-4: Rayleigh Scattering



Comparable or better sensitivity than CMB-S4, with a first detection of Rayleigh scattering ~8 years faster

Platform for Future Technology

- Modular optics tubes enable upgrades to *any* detector that uses RF readout
- Mm-wave KID spectrometers demonstrated in SPT-SLIM could be installed when available (see K. Karkare talk this session)
- Dedicated access to SPT in world's most stable site for mm-wave observations provide unique environment to demonstrate these technologies



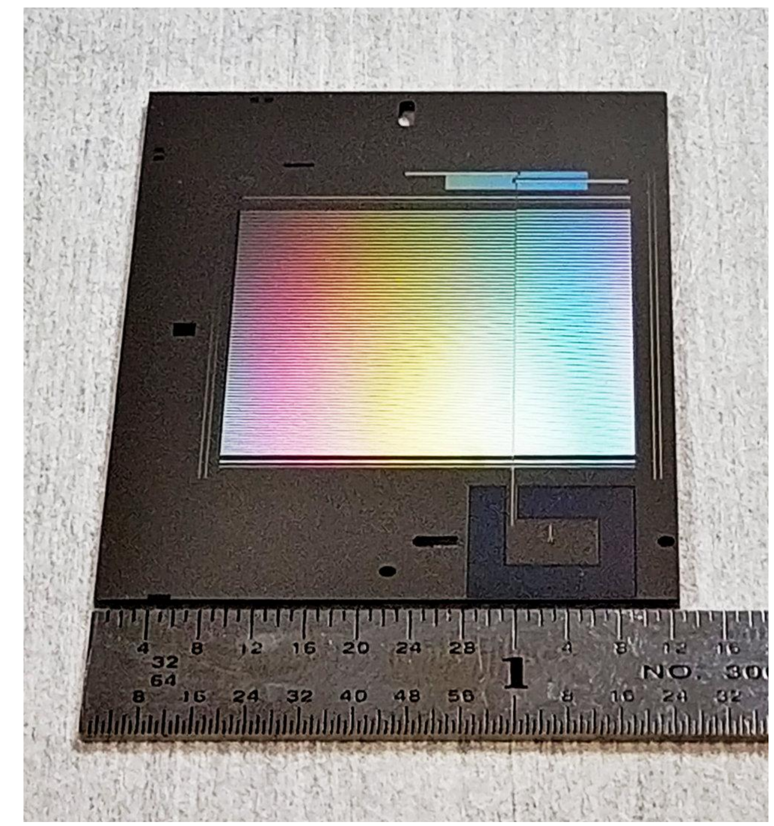
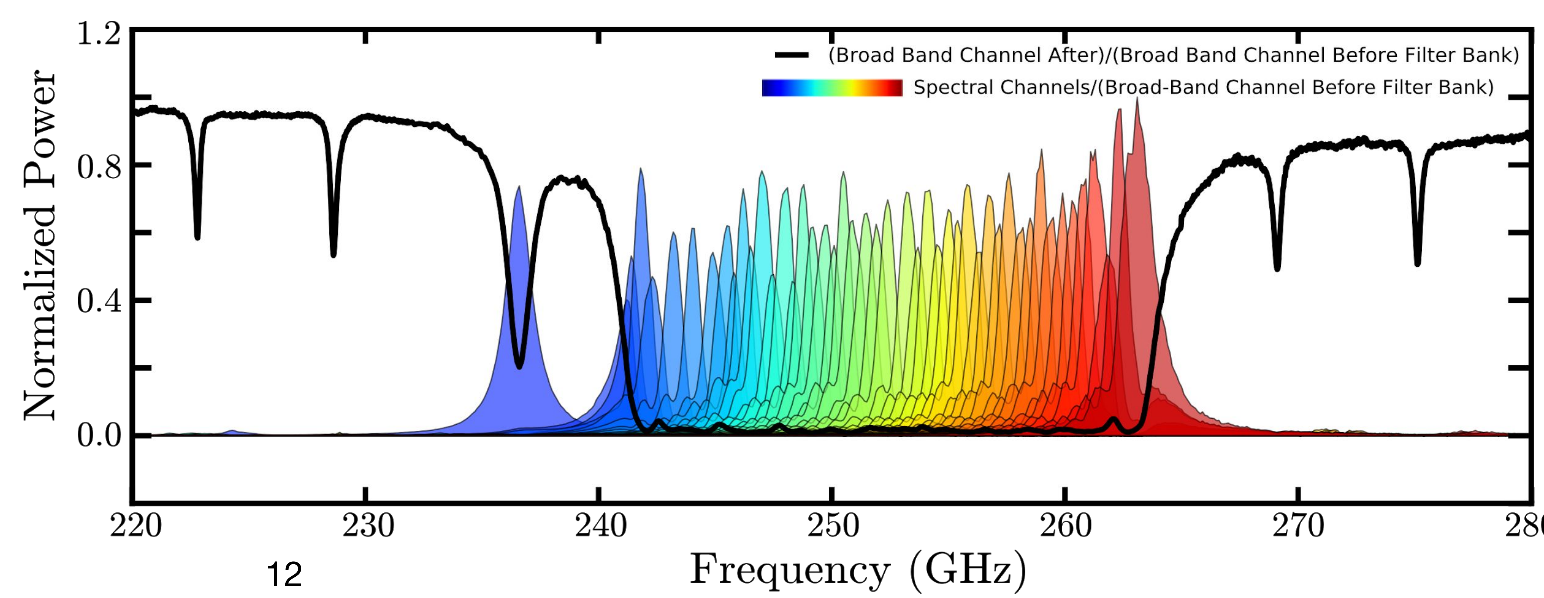


Figure: Erik Shirokoff



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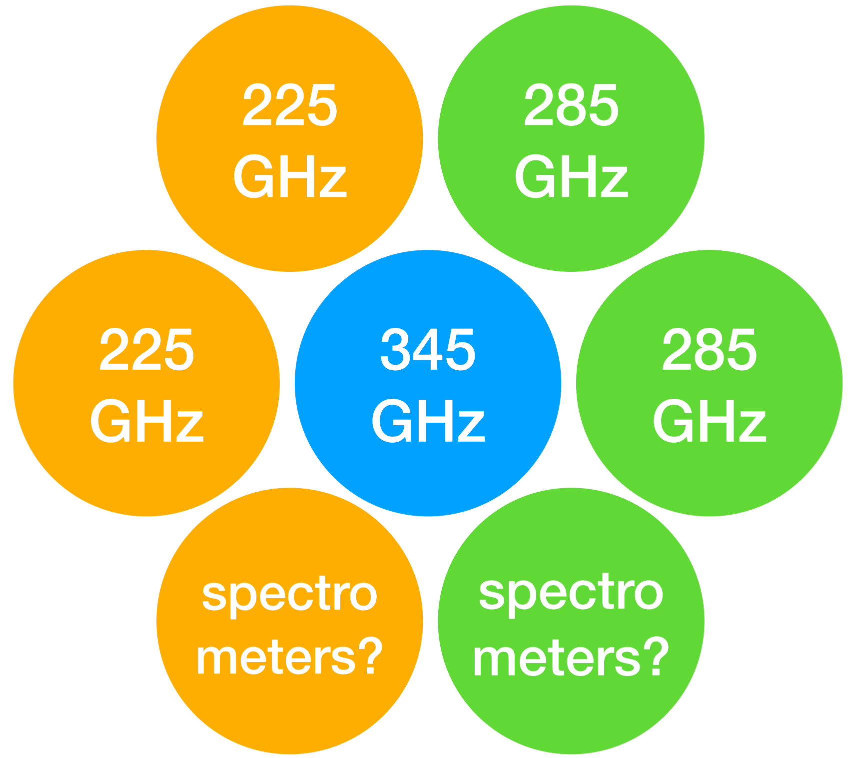

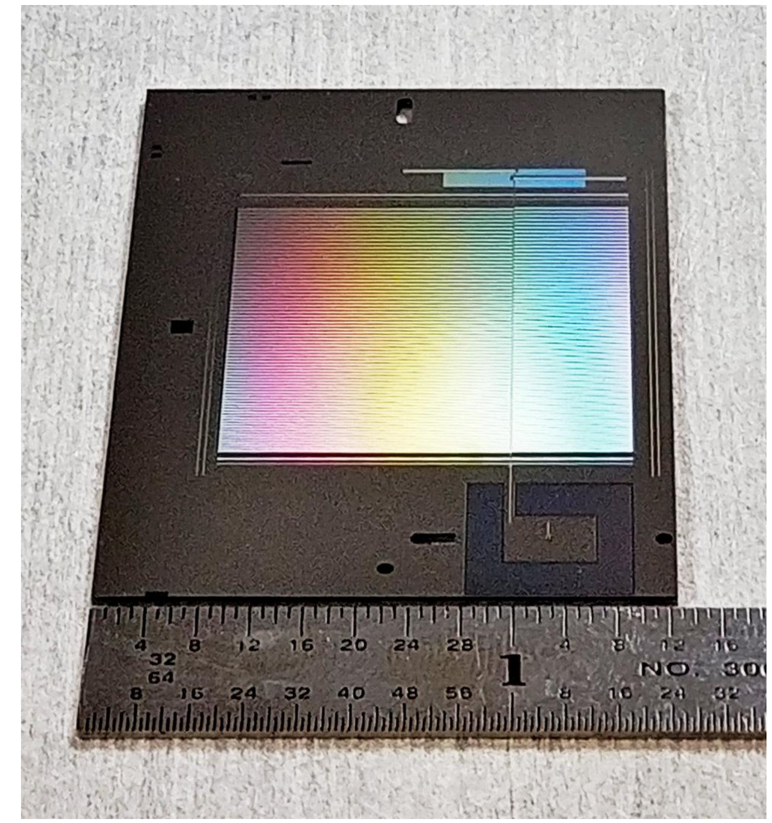

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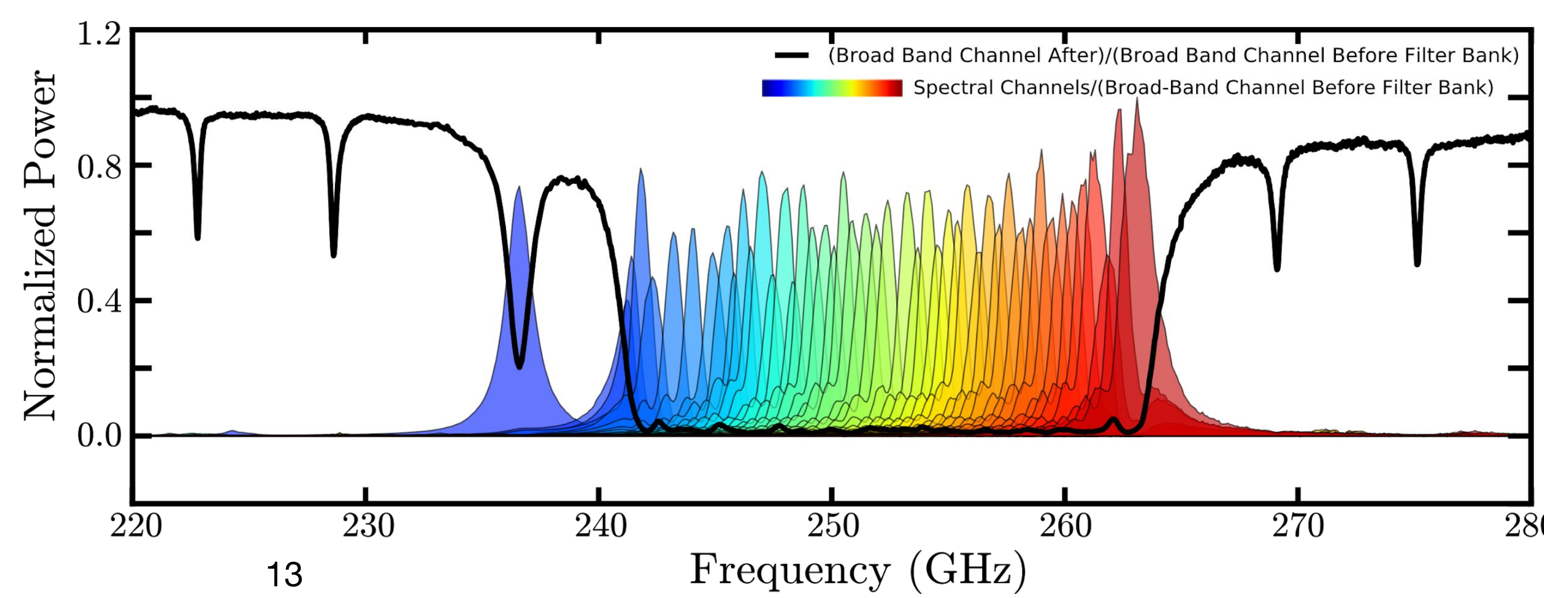


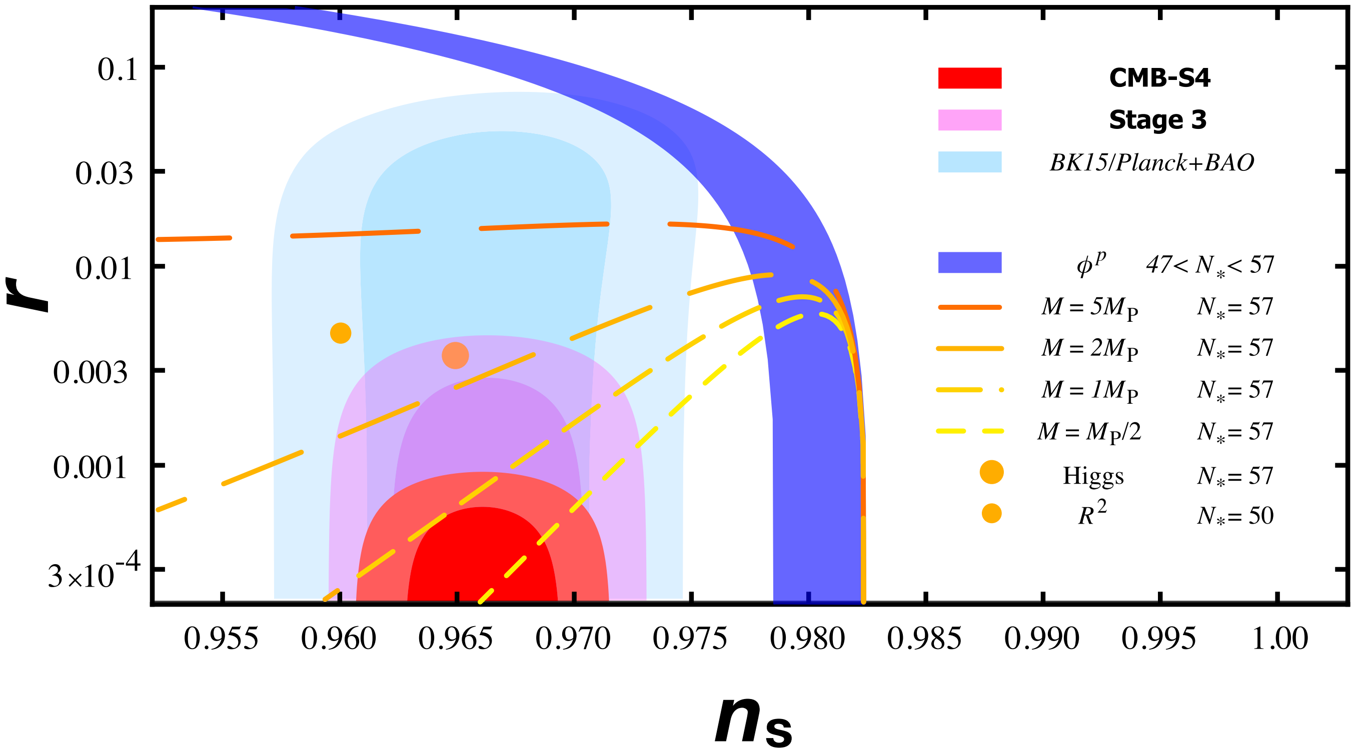
Conclusions

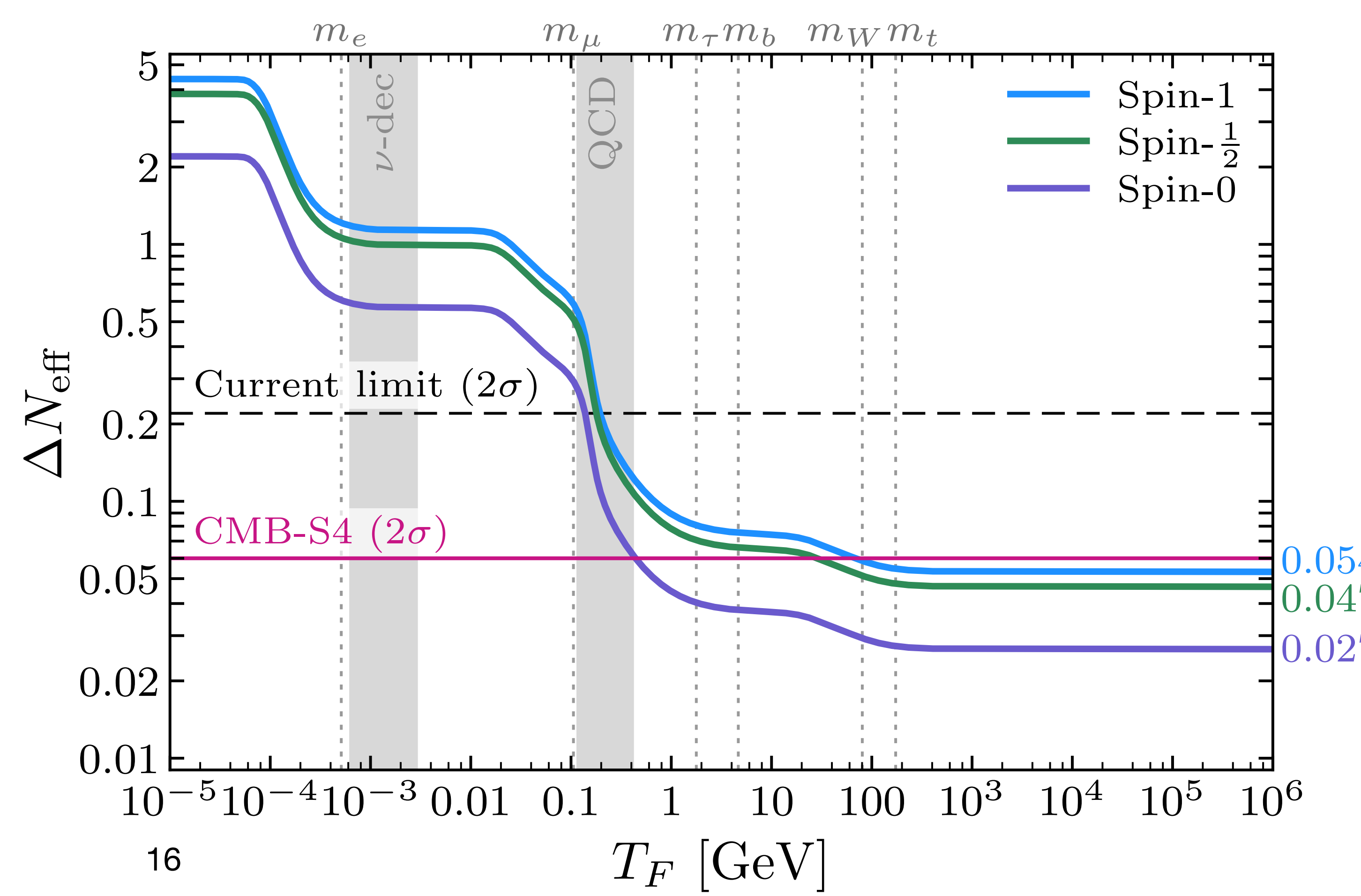
- Rayleigh scattering and precision measurements of the kSZ effect are powerful probes of the physics of recombination and reionization
- Background-limited MKIDs offer a fundamental sensitivity advantage vs. TESs for observations above 150 GHz
- Using a simple MKID architecture and modern highly multiplexed readout, SPT-4 is able to reach Rayleigh scattering and kSZ sensitivities comparable to CMB-S4 ~8 years sooner
- SPT-4 cryostat is a valuable platform for demonstrating early-stage detector technology

Backup

CMB Science Goals

- CMB experimental landscape in the 2020s is dominated by CMB-S4 and its predecessors (e.g. SPT-3G, BICEP Array, Simons Observatory)
- Broad science capabilities, but increasingly narrowly optimized for inflationary B-modes (r) and light relics (N_{eff})
- Common experimental design:
  - TESs observing at 27-270 GHz, with complex cryogenic multiplexing electronics
  - Mix of large 5-10m aperture telescopes, and small 0.5m refractors
- For CMB-S4, conservative and costly design choices have generally been emphasized to reduce risk and eliminate R&D… ***opportunities to innovate still exist!***





Survey Parameters

Survey	Area [deg^2]	225 GHz T noise [μK-arcmin]	225 GHz fwhm [arcmin]	285 GHz T noise [μK-arcmin]	285 GHz fwhm [arcmin]	345 GHz T noise [μK-arcmin]	345 GHz fwhm [arcmin]
Main	1500	2.9	0.8	5.6	0.6	28	0.5
Galactic	7000	13	0.8	25	0.6	130	0.5

kSZ ILC Residuals